

Estimating heating times of wood boards, square timbers, and logs in saturated steam by multiple regression

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Abstract

Heat sterilization is used to kill insects and fungi in wood being traded internationally. Determining the time required to reach the kill temperature is difficult considering the many variables that can affect it, such as heating temperature, target center temperature, initial wood temperature, wood configuration dimensions, specific gravity, and moisture content. In this study, the time required to heat the center of round, square, and rectangular wood members in saturated steam was calculated by using heat conduction equations for a number of combinations of these variables. The resulting heating times were then fit to multiple regression models, resulting in regression equations that provided a calculation method that is easier and more convenient to use than the heat conduction equations, especially considering the many combinations of the independent variables that might be of interest in heat sterilization treatments for killing insects and pathogens. Deviations between the times calculated by regression and those calculated by the heat conduction equations averaged less than 10 percent. The regression models appear to offer sufficiently good estimates of heating times to be useful in planning heat sterilization activities.

Heat sterilization of wood in various configurations is currently used as a precaution to prevent insect and pathogen transfer between countries in international trade. Current regulations call for holding the center of any wood configuration at 133°F (56°C) for 30 minutes. Future research may identify other time-temperature regimes required to kill specific insects or fungi. An important question in heat sterilization is the time required for the center of the wood configuration to reach the kill temperature. This heating time varies widely depending on several factors: wood specific gravity (SG), moisture content (MC), cross-sectional dimensions and configuration, heating temperature, initial temperature, target center kill temperature, heating medium (wet or dry heat), and stacking method. The objective of this paper is to present a relatively simple method for calculating heating time estimates where SG, MC, wood dimensions, and the relevant temperatures are the variables involved.

A previous report (Simpson 2001) showed that the heat conduction equations developed by MacLean (1932) work well in calculating heating time estimates when the heating medium is saturated steam (in practice, a wet-bulb depression of no more than about 2° to 3°F (1.1° to 1.7°C)). As the wet-bulb depression increases and the heating medium becomes dryer, actual heating times become progressively longer than those calculated by the MacLean equations (Simpson 2002, 2003a, 2003b; Simpson et al. 2005). The reason for this in-

creased heating time is that in a dry heating medium, water is evaporating from the wood surface, which cools the surface. This reduced surface temperature in turn reduces the driving force for heat transfer and therefore slows heating. While it is invalid to apply the MacLean equations using the air temperature of a dry heating medium, the use of wet heat is the most practical approach because it does minimize heating time and allow calculation of useful estimates of heating times. In addition, Simpson et al. (2005) found that when the wet-bulb depression was about 10°F (5.6°C), the wet-bulb temperature can be used in place of the dry-bulb temperature in the MacLean equations and produce good estimates of heating time.

The MacLean equations for rectangular and round cross sections and the equations for calculating thermal properties from wood temperature, SG, and MC (above the freezing point of water) are given in Simpson (2001). This report (Simpson 2001) also includes a series of tables of heating times for various cross-sectional dimensions, SGs, MCs, heating temperatures, initial temperatures, and target center tem-

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peratures. The tables include combinations of the following variables:

MC – SG combinations:

25, 70, 100, 130 percent MC at SG 0.35

25, 70, 100 percent MC at SG 0.45

25, 70 percent MC at SG 0.55

Heating temperatures:

140°, 150°, 160°, 170°, 180°, 190°, 200°F (60.0°, 65.6°, 71.1°, 76.7°, 82.2°, 87.8°, 93.3°C)

Target center temperatures:

133°, 140°, 150°, 160°, 170°, 180°F (56°, 60.0°, 65.6°, 71.1°, 76.7°, 82.2°C)

Diameter of round cross sections:

4 to 16 inches in 1-inch intervals (102 to 406 mm in 25-mm intervals)

Sides of square cross sections:

3 to 16 inches in 1-inch intervals (76 to 406 mm in 25-mm intervals)

Width and thickness of rectangular cross sections:

Various combinations ranging from 4 to 12 inches (102 to 305 mm) wide and 0.70 to 4 inches (18 to 102 mm) thick

There are many combinations of the variables. It was impractical to include them all in the previous report (Simpson 2001), and it is likely that combinations of variables not included might be of interest. One approach is to use the equations for calculating thermal properties and the MacLean equations to calculate heating times for these combinations. These calculations are quite cumbersome and tedious to make unless they are done in a computer program. They do not lend themselves to use in a spreadsheet.

Multiple regression analysis

Another approach is to calculate heating times using the heat conduction equations for a large number of combinations of the variables and fit them to a multiple regression model. Multiple regression coefficients can then be developed that make calculations of estimated heating times for any combination of the variables relatively simple and ideally suited for use in a spreadsheet. Two general forms of empirical regression equations were considered: 1) an additive combination of the individual variables, each raised to a regression coefficient power; and 2) a multiplicative combination of the independent variables, each raised to a regression coefficient power. The multiplicative combination resulted in the highest coefficient of determination and was therefore used for the analysis. The following multiple regression models were developed for heating in saturated steam.

Round or square cross sections:

$$t = a(T_{ht})^b(T_{ctr})^c(T_{init})^dD^eM^fG^g$$

Rectangular cross sections:

$$t = a(T_{ht})^b(T_{ctr})^c(T_{init})^d(TH)^eW^fM^gG^h$$

where t = estimated time for the center to reach target temperature (min); T_{ht} = heating temperature (°F); T_{ctr} = target center temperature (°F); T_{init} = initial wood temperature (°F); D = diameter of round cross section or side of square (in.); TH = thickness of rectangular board (in.); W = width of rectangular board (in.); M = MC (%); G = basic SG; $a \dots h$ = regression coefficients.

Table 1. — Multiple regression coefficients and coefficients of determination for wood member heating time data analysis.

Coefficient	Cross-sectional dimension		
	Round	Square	Rectangular
a	38.41	45.36	60.44
b	-2.969	-2.954	-3.032
c	3.013	2.996	3.080
d	-0.2626	-0.2616	-0.2662
e	2.000	2.000	1.720
f	-0.0946	-0.0946	-0.2560
g	0.2157	0.2158	-0.0945
h	--	--	0.2156
r^2	0.989	0.991	0.992

The number of combinations of variables included in the multiple regression analysis for round cross sections was 12,636. The first attempt for square timbers and rectangular boards included both configurations in one analysis. Despite a high statistical coefficient of determination (r^2) of 0.993, the combined model resulted in large deviations between some heating times calculated with the regression coefficients and those calculated using MacLean's equation. After this, the rectangular cross section analysis was divided into two separate analyses: one for perfect squares where both cross-sectional dimensions were exactly the same and the other for boards whose thickness and width were different. The number of combinations of variables was 10,692 for perfectly square cross sections and 22,356 for rectangular boards. The regression coefficients and coefficients of determination are shown in **Table 1**. The high values (0.99) for the coefficients of determination indicate a good fit of the MacLean times to the models.

Another evaluation of the fits is to compare the deviations of heating times calculated by the regression models from those calculated by the MacLean equations. The average deviations between the two were 5.9, 5.8, and 9.9 percent for the round, square, and rectangular cross sections, respectively, with corresponding SDs of 0.45, 0.47, and 5.47 percent, respectively. The round and square cross sections had uniformly low deviations, so the regression equations gave excellent estimates of the heating times calculated by the MacLean equations. The results were not quite as good for the rectangular boards. Although the overall average deviation of 9.9 percent is reasonably good agreement, the SD of 5.47 percent is high, and some individual deviations were as high as slightly more than 20 percent. However, considering the natural variability of wood and its effect of causing heating times to vary and the fact that the MacLean equations themselves are only estimates of heating times, it seems that the regression models offer sufficiently good estimates of heating times to be useful in planning heat sterilization activities.

The results presented so far do not address the issue of when a rectangular cross section should be treated as a square or as a nonsquare rectangle in terms of which regression model and coefficients to use. For example, which model should be used for a timber that deviates only slightly from a perfect square? Should the heating time of a timber measuring 4.00 by 4.25 inches (102 by 108 mm) be calculated by the regression model and coefficients of the square or the rectangle in **Table 1**? In other words, how far from a perfect square can a timber devi-

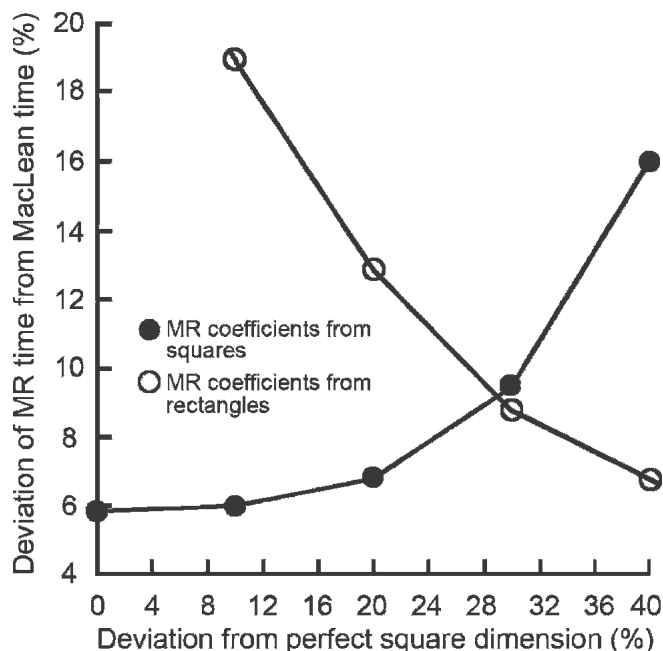


Figure 1. — Effect of deviation in dimension from a perfect square on the deviation between heating times calculated by multiple regression (MR) and by the heat conduction equations of MacLean (1932).

ate before the model and coefficients should be changed from the square to the rectangular mode? Or conversely, as the cross-sectional dimensions of a nonsquare rectangle approach those of a perfect square, at what point should the model and coefficients be changed from the rectangle to the square mode? **Figure 1** addresses this issue, where the deviation of the regression time from the MacLean time is plotted against the deviation of a timber from a perfect square. Two curves are shown: one is the time deviation of rectangles that deviate from a perfect square as calculated with the square regression model (using the average of the two cross-sectional dimensions), and the other is the time deviation of rectangles that deviate from a perfect square as calculated with the rectangle regression model. When a timber deviates from a perfect square by 10 percent (for example a nominal 6- by 6-in square that is actually 6.0 by 6.6 in), the calculated heat-

ing time using the square regression model will differ from the time calculated with the MacLean equation by about 6 percent. When a timber deviates in dimension from a perfect square by about 30 percent (for example, a nominal 4- by 4-in square that is actually 4.0 by 5.2 in), either model will give an overall average time deviation of about 9 percent, which is the point where the two curves intersect. In other words, the models will be equal in terms of estimation ability. The practical suggestion from **Figure 1** is that if a timber deviates from a perfect square by less than about 30 percent, use the regression model and coefficients of the square. If deviation is greater than 30 percent, use the regression model and coefficients of the rectangle.

Conclusions

The multiple regression analysis used in this study was successful in offering estimates of heating times that are reasonably close to those calculated by heat conduction equations developed by MacLean for wood heat sterilization in saturated steam. The regression equations provide a calculation method that is easier and more convenient to use than the heat conduction equations. Many combinations of variables were considered in the equations, such as heating temperature, target center temperature, initial wood temperature, wood configuration dimensions, SG, and MC. The regression models appear to sufficiently estimate heating times and would therefore be useful in planning heat sterilization of wood.

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